Deployable Optics for Earth Observing Lidar Instruments

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***Abstract*-This paper presents an overview of the Deployable Optics Modeling Experiments (DOME), Advanced Component Technology (ACT) project. DOME is developing and advancing to flight readiness precision deployable optics technology for space-based lidar instruments. The overall objective is to enable low cost, passively deployed mirrors for UV-DIAL instruments from 2 meters to 10 meters in diameter. The key technologies include high precision deployment mechanisms with submicron level stability and precision. The project includes experimental verification of models that predict the on-orbit precision and stability of a deployed mirror petal. This includes verification of models of the nonlinear microdynamic stability, deployment repeatability, and mechanical hysteresis. Even though the technology is being tested at UV wavelengths for potential UV-DIAL applications, it has wide ranging applications for UV, visible, near- and mid-IR lidar systems in DIAL as well other lidar systems for atmospheric species, aerosols, clouds, and direct detection wind systems. DOME technology has application to space-based astronomical instruments as well.**

I. INTRODUCTION

Precision deployable reflectors for space-based telescopes will be a key space engineering challenge for the next several decades. Such deployable reflectors are envisioned for a variety of missions, from Earth observation to space astronomy. Whether they operate in IR, visible or UV, all these applications share similar requirements for extremely stable and accurate deployed configurations.[1-3]

The engineering challenge is to achieve the necessary stability and accuracy for lowest overall system cost. Perhaps the most significant cost savings is realized by deploying the telescope rather than launching it in its final configuration (as was the Hubble). Most large space structures are not mass constrained but volume constrained. Deployment makes the best use of the available launch vehicle payload capacity. [4]

Deployment, however, brings with it many system level trades that make the cost prohibitive if not properly considered. Deployment implies the structure is articulated in some fashion, having mechanisms that impart degrees of freedom and allow motion. The parts of the structure must move through many meters of motion, ending up within very tight tolerances, often less than a few microns of the intended position. Once deployed, the structure must hold its position, that is "remain stiff and stable," within the necessary tolerance even under on-orbit loads.[1] This is where the critical trades interact.

The need for stiffness and stability once deployed can only be met by deployed structural "depth" that resists deformation. [5-7] In fact, the problem is not so much one of unfolding the mirror of the telescope, for that is commonly a nearly "two dimensional" kinematic problem. The major problem is deploying the deep structure that supports the mirror. That is a three dimensional kinematic problem. In other words, the stowed configuration must be expanded in all directions to achieve the final shape and function. This means more articulation in the deployment, which further increases complexity and risk.

In the case of deployed radio frequency (RF) reflectors, the state of the art can deploy structures with perhaps part per 1,000 or part per 10,000 overall stability and precision. [8] In other words, a 10-meter diameter RF antenna might be deployed and stabilized to within a fraction of a millimeter to a few millimeters. This is sufficient for RF applications. But for precisions necessary for optical instruments, pushing beyond this limit requires special attention to the design of the mechanisms [9,10]. Phenomena arise below 100 microns of resolution due to the small-scale friction and anelasticity in the mechanisms and materials. This is known as "microdynamics" in the literature [11].

So a natural trade arises between the complexity of the deployment, the deployed stiffness in the structure, the sophistication of the mechanisms, and the use of active adjustment and control technologies. In a complex trade like this, it is important to understand what defines the limits of each element in the trade, and then work to improve that limit as needed.

In the late 1990's, NASA Langley Research Center (LaRC) and the University of Colorado (CU) initiated a

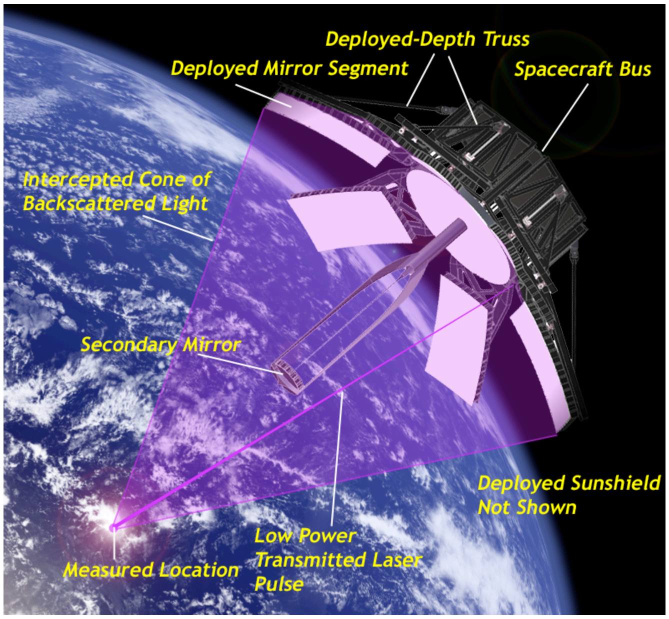

Figure 1. Concept for a space-based lidar telescope receiver.

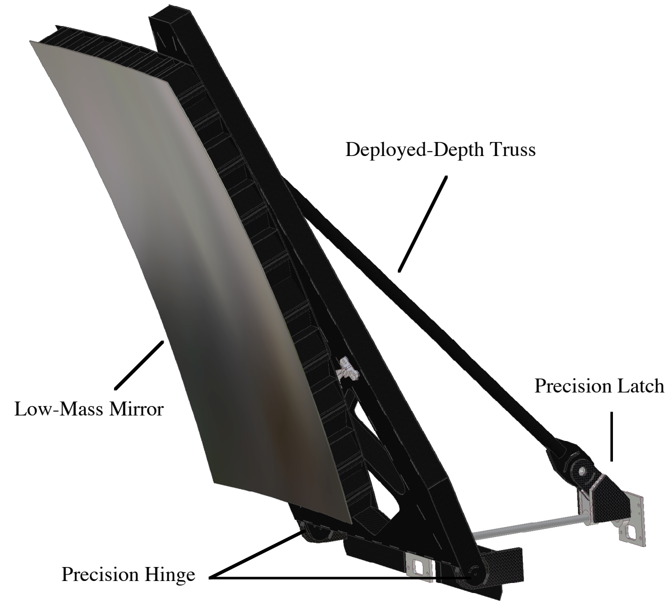

Figure 2. Single-petal test article extracted from the six-petal concept. DOME is performing experiments on this test article to validate models if its precision and stability at submicron levels of motion.

cooperative research program to investigate this question. It was explored in the context of a deployed lidar receiver for atmospheric science applications. This program developed both design principles and hardware for optically stable mechanisms such as hinges and latches. These principles were embodied in a deployable telescope concept developed by Composite Optics, Inc. [12]. The deployed telescope concept is shown in Figure 1. The overall diameter of this particular telescope is approximately 2.5 m^2. A single petal of this structure was actually built (Figure 2). Details of the mirror and deployed structure construction can be found in [12], and the results of an initial experiment can be found in [13].

Small in overall dimension, (it was intended for a Pegasus launch vehicle), this telescope was in fact a "large space structure" from the point of view of mechanics and dynamics. Its deployment sequence is somewhat more complex than early concepts for the James Webb Space Telescope (JWST) [3]. The key advantages of this lidar design were the use of low hysteresis mechanisms and a deployed depth mirror support structure. *These two factors together meant that this concept is perhaps 50 times the relative overall stability and precision of comparable JWST technology*. In principal, this concept represented a substantial advancement in state-of-the-art. Whether this was to be realized remained to be proven.

In 2002, CU and LaRC proposed a program for the Advanced Component Technology (ACT) program within the NASA Earth Science Technology Office (ESTO). This project is known as DOME for Deployable Optics Modeling Experiments. The overall goal of DOME is to perform the experimental verification necessary to advance this precision deployment technology to flight readiness.

The purpose of this paper is to describe the overall approach and engineering science being developed under DOME. This documents the progress in the project at the beginning of the second of three years of development. The remainder of the paper is organized as follows. Section II provides an overview of the science background and needs of the intended applications of the technology. Section III describes the overall DOME experimental objectives and top-level requirements. Section IV describes the current design of the DOME experiment systems.

II. Science Background and Need

A key influence on the definition of the DOME objectives and requirements has been close attention to the science application needs. For instance, DOME includes extensive modeling activities that extrapolate ground-based measurements to predicted system-level performance on orbit. This includes predictions of nonlinear ground-to-orbit changes in the structural mechanics and dynamics, measurement uncertainty, and modeling uncertainty. All these are to be linked to a prediction of the function of the science instrument. The subsections that follow describe the overall background and requirements derived from the science instrument application.

A. Application to Space-Based Lidars

Ground and aircraft-based lidar (laser radar) systems have demonstrated excellent capability for measuring atmospheric gas species, and aerosol and cloud distributions. The advantages of lidar measurements are their relatively high spatial resolution, high measurement specificity (avoiding interference from other gases), lack of dependence on external light sources, and relatively simple inversion methods compared to retrieval methods used in passive remote sensing. Because of their capability to provide global coverage including over oceans and remote locations and their excellent spatial resolutions, NASA and other national and international agencies are attracted to the deployment of the lidars from space. However, long ranges from space to the atmosphere require high power lasers and large collection area receivers to retain the signal-to-noise ratio and the quality of measurements provided by terrestrial lidar systems.

Demonstration of deployable telescope technology is one of the key elements of lidar technology that is required for the development of future space-based lidar systems like the one for the measurement of tropospheric ozone (O_3) profiles [14,15]. Atmospheric O_3 plays a key role in atmospheric chemistry, global warming, and in characterizing atmospheric transport/dynamics—the issues linked to our understanding of global atmospheric processes and their evolution. Global tropospheric measurements of O_3 from space are needed to analyze, characterize, and assimilate into global prediction models for a better understanding of many of the atmospheric processes and for predicting future trends [16-18].

Strong scientific evidence is available to support the development of global tropospheric profiling system that is not available at present. Recent investigations using ozonesonde measurements along the Asian Pacific Rim using a global 3-D chemical transport model (GEOS-CHEM) at Harvard [19] have revealed a number of sources for tropospheric ozone including those due to biomass burning, anthropogenic pollution, stratospheric-tropospheric exchange, convection, and lightning. From these studies valuable information can be obtained about many atmospheric chemical processes. Differential Absorption Lidar (DIAL) systems have been widely used to study O_3 and aerosols that can then be used to monitor and study many of the atmospheric processes. DIAL measurements of stratospheric O_3 from ground stations [20-22] are routinely carried out to monitor and study many stratospheric O_3 processes. NASA Langley's airborne DIAL measurements of O_3 [23] have been used in field experiments over many region of the world during the past twenty years and demonstrated their application to a broad range of process studies in the atmosphere. While these studies can be considered as the 'new frontier' in the studies of the troposphere, there are at present, however, no global measurements of tropospheric O_3 that cover the entire globe. Passive remote sensing measurements by Stratospheric Aerosol and Gas Experiment II (SAGE II) and Microwave Limb Sounder (MLS) have provided excellent coverage of the stratosphere but only limited coverage in the troposphere. NASA's Global Tropospheric Experiments have shown that tropospheric atmosphere is high structured and consists of narrow 1-3 km size layers [24-26]. Even planned future missions like Aura are expected to provide coarse resolution in the troposphere.

Development of large-area, lightweight, and compact (on launch) receiver system technologies would enable and enhance future space-based lidar missions. In particular the DIAL technique is well suited for measuring atmospheric O_3, H_2O, and CO_2 profiles along with simultaneous aerosol measurements. Future space-based direct detection wind lidar systems would also benefit from deployable telescope systems. Lidar signals decrease as the square of the distance to the target range and, consequently, space-based measurements require a combination of high-energy lasers, large area receivers, and efficient optical detection systems. Deployable telescopes offer the largest enhancement factors for space based lidar signals. For example, a 2.5-m class deployable telescope would provide an effective area of about 3.5 m^2, which is over five times that of a conventional 1-m diameter telescope like that used in the LITE (Lidar-in-space Technology Experiment) and planned missions like GLASS (Geoscience Lidar Altimeter System) and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations), and about 35 times that of conventional airborne lidar systems. Increased area receiver systems will also have other beneficial consequences: they increase lidar signals without increases of laser power that would otherwise elevate laser eye safety issues particularly in the visible and near IR regions.

Development of deployable telescope technology for space application would have wide ranging lidar applications in future lidar missions including those that will be follow on to CALIPSO and GLAS, and enable other DIAL missions like those to measure global O_3, H_2O, and CO_2 profile distributions that are needed to study many climatic, chemical, and dynamical processes and for improvements in our understanding of the global water and carbon cycles.

B. System Requirements

The long ranges to the aerosol and/or molecular targets in the atmosphere from the space vantage point are particularly hard on active remote sensors such as lidar. This is because the laser energy incident on the target spreads out on its way from the target back to the lidar. The magnitude of the enhancement of the signal for space-based lidar systems can be appreciated by the fact that an enhancement of signal by a factor of 352 or 1225 is needed to replicate the performance of airborne system operating from an altitude of 10 km and making measurements near the ground compared to making the same measurements from a satellite at an altitude near 350 km. Based upon the projected improvements in laser, detector, and optical throughput of future lidar systems and the improvements due to the gain in the signal-to-noise due to increased data averaging, a minimum diameter of a segmented telescope needed to enable a space mission was identified as 2.5 m [15]. Limited by the launch vehicles, such lidar systems will have to resort to segmented, deployable, mirror panels to provide the required aperture area for collection of return photons. The mirror panels must be lightweight not just for meeting the launch constraints, but also for avoiding the distortions of mirror panels and their structure after deployment under 0-g condition [12]. The deployable telescope systems will be applicable to a broad class of direct detection lidar systems that will, in general, use small area single element solid-state detectors with diameter about 0.5 mm. Consequently the maximum allowable spot size at the focus has to be limited to a circle of diameter of about 0.5 mm.

III. Experiment Objectives and Requirements

The overall objective of the DOME project is to develop and bring to flight readiness essential component technology for the deployment of Earth observing lidar telescopes. This consists of three primary technical elements and objectives described in the next 3 subsections.

A. Precision Latching

Prior testing of the single-petal test article discovered significant deployment precision error due to the design of the latch preloading mechanism. This was reported in [13].

The objective of this project element is to develop a new latch that replaces the original latch. The new latch will have micron level intrinsic repeatability, high stiffness and low hysteresis. This is being done using the theory of mechanism development reported in [9] and [10], along with the deployment repeatability reported in [27].

A key element in this part of the project is that the performance of the latch be predictable by design analysis, not by trial and error. The models will be verified at both the component level and the overall system level.

B. Sub-System Verification of Deployment Precision and Stability

The objective of this element is to develop and implement an experiment that verifies the deployment precision and stability of the single-petal lidar test article in multiple gravity orientations.

Verification in multiple gravity orientations is a common technique applied to lower precision radio frequency antennas. By showing that the deployment repeatability and stability satisfy required tolerances in orthogonal gravity orientations, it is expected this will bound the deployed shape and stability in 0-g. This depends on the predictability of the deployment mechanisms, and on the fidelity of the models. Such a measurement is also a minimum requirement to determine whether further testing in 0-g would be required for the technology. If successful, the techniques may also provide validated verification methods for deployed optical flight systems.

C. Theoretical Modeling

The objective of this project element is to develop a theoretical model, correlated with the above experiments, which can be used for specifying requirements and tolerances on a future flight lidar system. This includes linking the model inputs to real flight conditions (including 0-g) and linking the model outputs to the actual science instrument performance.

This modeling objective is essential to be able to trace the results of the experiments to the intended application. The key challenge to this task will be the incorporation of nonlinear mechanical and material behavior and other microdynamic effects. Also, the modeling methodology developed to meet this objective would also enable the verification of spacecraft telescopes too large to practically test on the ground.

D. Technology Products

The intended products of the DOME project are as follows:

- Validated precision latch hardware, including experimental uncertainty estimates
- Validated single-petal telescope component hardware, including experimental uncertainty estimates
- Validated modeling methodology for precision latches, including model uncertainty estimates
- Validated modeling methodology for precision hinges, including model uncertainty estimates
- Validated modeling methodology for integrated opto-mechanical systems, including model uncertainty estimates

IV. Experiment and Modeling Concepts and Approach

The DOME project will accomplish the above objectives through a combination of experimental and analytical activities. These are defined in the following subsections.

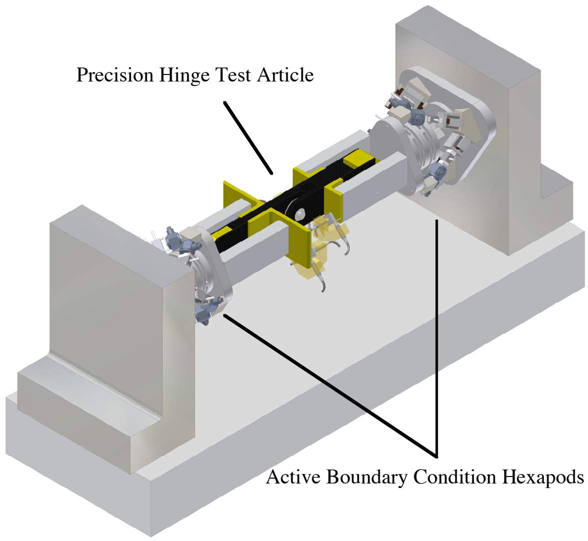

Figure 3. Rendering of the component test apparatus.
A hinge test article is shown. Forces simulating the compliance at the boundaries of the component are imparted by 12 DOF active boundary condition hexapods.

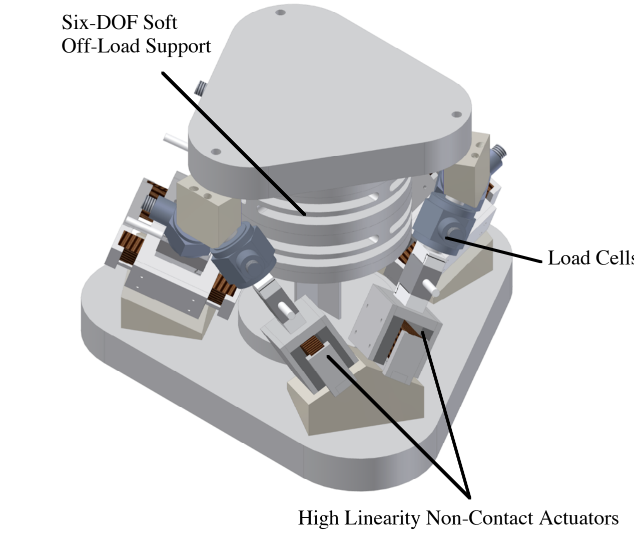

Figure 4. Rendering of the COIL active boundary condition hexapods. These provide 6 DOF of actuation at boundary points for both the component and the single-petal experiments.

A. Component Experiments

Component experiments will be developed to validate the mechanical performance of selected components of the single-petal test article. A rendering of the component test apparatus design is shown in Figure 3.

Component test articles will include the mechanical latch design described in Section III.A above. They may also include other components of the single-petal test article that are determined to have model uncertainty significant enough to justify the experiment. Currently, this includes the precision hinges, but may also include material coupons.

The component experiments will control and vary as appropriate:

(a) the thermal environment

(b) the deployment state history, and

(c) the elastomechanical boundary conditions and loads

These will be consistent with the actual in situ influences the component experiences within the structure so as to facilitate the modeling of the component within the structure.

A unique approach has been developed for actuating this experiment. Because of the nonlinearity inherent in the mechanism mechanics and dynamics, the boundary conditions during the test become important considerations in the interpretation of the results. We have developed a technique known as COIL (Component-in-the-Loop), which simulates the compliance of the rest of the structure at the boundaries of the component test. This was reported in [28]. Figure 4 shows a rendering of the COIL actuation hexapods. Each hexapod controls six degrees of freedom (DOF) of forces and moments at a given boundary location.

B. Single-Petal Experiment

The single-petal experiment is intended to validate the mechanical performance of the single-petal test article with the new latch design. A rendering of the single-petal experiment is shown in Figure 5 below.

The single-petal experiments will control and vary as appropriate:

(a) the thermal environment

(b) the gravity orientation

(c) the deployment state history

(d) the elastomechanical boundary conditions, and

(e) the preload in the latch mechanism.

Two sets of measurements have been designed:

- Performance-related measurements: Structural DOF that determine the optically relevant shape and position of the mirror front surface relative to the

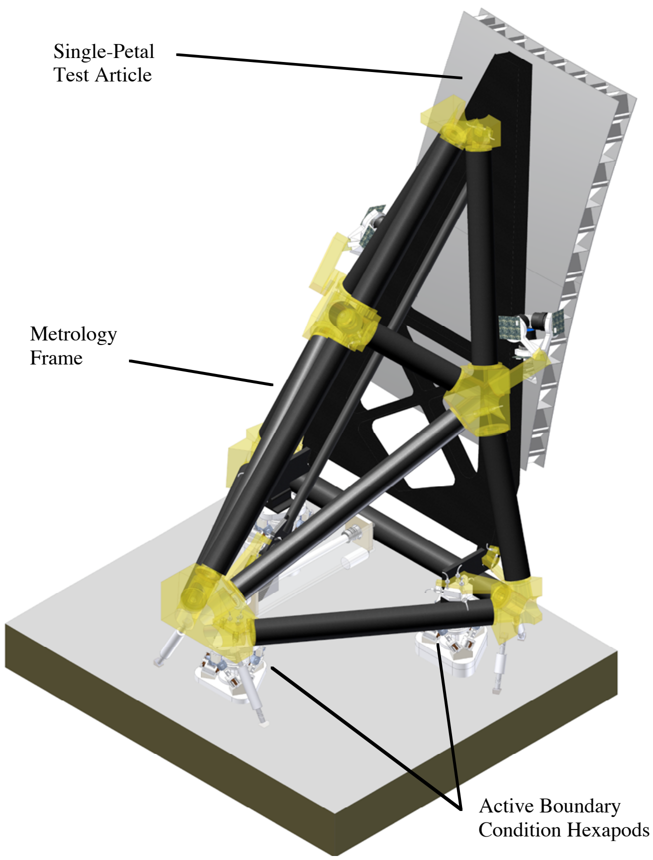

Figure 5. Rendering of the single-petal experiment apparatus.

interface between the single-petal test article and its intended attachment to the remainder of the telescope.

- Modeling-related measurements: Structural DOF that provide sufficient information to determine likely sources of error within a comparative model of the experiment.

These DOF will be measured with respect to a highly stable metrology frame that rests behind the test article, as indicated in the rendering. The metrology frame is designed to have both high thermal and vibration stability. Deviations less than 20 nanometers in any axis at all measurement locations are expected.

The measurement sensors include high precision accelerometers and eddy current sensors. In addition, the experiment uses a special, high-resolution videometry system with 10-20 nanometer accuracy. This videometry system provides a second witness to the static stability and deployment repeatability measured by the eddy current sensors.

As in the component tests, the single-petal tests also incorporate active boundary condition COIL hexapods. These are attached at three locations, providing 18 DOF of boundary condition control. Not shown in the figure is a load application frame that supports 2 additional actuators that apply loads to the tip of the test article. This will be used to test the hypothesis that the effect of gravity is identical to the effect of static stress induced in the structure and the deployment mechanisms.

C. Models

The DOME project will develop and apply the following theoretical models:

- Component Models: Predict the observations of the component experiments

- Single-Petal Model: Predicts the observations of the single-petal experiment.

- Flight System Model: Predict the performance of the full six-petal deployable telescope in zero gravity.

Each model includes tolerances on the prediction for comparing with the statistical descriptions of the experimental data. Once the component models have been correlated with the component experiments, these are then incorporated into the single-petal model. Likewise, once the single-petal model has been correlated with the single-petal experiments, it is incorporated into the flight system model. This results in a prediction of the flight system performance including statistical estimates of the uncertainty. The output of this flight system model will be a prediction of the optical system performance.

V. Conclusions

This paper has reviewed the objectives and design of the Deployable Optics Modeling Experiments ACT project. The overall objective of this project is to advance key technology for the deployment of space-based lidar receivers from 2 to 10 meters in diameter. The project is developing a series of component and subsystem experiments, correlated with models, that will lead to a prediction of on-orbit performance of the telescope.

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